

External temperature effects on the hysteresis of NiTi wires in dampers for stay-cables

V. Torra, G. Carreras, S. Casciati, and C. Auguet

Abstract— The use of NiTi wires, one of the Shape Memory Alloy (SMA) materials that permits efficient damping in stayed cables for bridges, requires an appropriate behavior when exposed to the external temperature effects. The Clausius-Clapeyron thermodynamic equation establishes a shift of the hysteretic cycle in the stress-temperature representation of about 6 MPa/K for the used wires of diameter 2.46 mm. Hence, an adequate experimental study is necessary to characterize the temperature effects in working conditions. The conducted analysis is twofold. First, the practical evolution of the hysteresis cycle is investigated. The results suggest that the wire permits a completely satisfactory use for temperatures as low as 253 K (i.e., -20 °C). Second, the focus is placed on the effects of extreme winter actions (i.e., as low as 233 K or -40 °C). A preliminary stress aging process at 373K seems adequate to this requirement. Indeed, after the stress aging, the SMA wire increases their working domain by 300 or 400 MPa and the temperature domain is expanded by 30 – 50 K. Measurements visualizing recoverable dynamical actions in the SMA alloys are also outlined.

I. INTRODUCTION

Recent literature [1, 2] focuses on the application of shape memory alloys (SMA) as passive elements in dampers for structures via their hysteresis cycle. The functional properties of SMA are associated to a martensitic transformation (MT), which is a transformation between meta-stable phases [3, 4]. The use of SMA for damping in civil structures is studied with different targets; mainly, the mitigation of vibrations either induced by earthquakes in buildings or by wind, rain or traffic in stayed cables of bridges is pursued. For cables, the experimental studies carried out in facilities show that NiTi wires of diameter 2.46 mm work satisfactorily with a reduction of the oscillations amplitude of about 1/3-1/4 [5, 6, 7, 8]. The applicability of SMA in stay cables of bridges using their pseudo-elastic cycles in NiTi wires was investigated in facilities as the European Laboratory for Structural Assessment (ELSA) in Ispra, Italy and the Institut Français des Sciences et Technologies des Transports, de l'Aménagement et des Réseaux (IFSTTAR) near Nantes, France.

In particular, it was established that the behavior of a trained standard wire of diameter 2.46 mm with an S-shaped hysteresis cycle was suitable to moderate summer-winter temperatures, i.e., between 258 and 313 K, as found in Western Europe [5, 6]. The external temperature modifies the hysteresis cycle in the stress-strain coordinates by a shift in the stress coordinates which is proportional to the temperature change through the Clausius-Clapeyron thermodynamic coefficient (CCC). Starting from a null stress condition at the test initial temperature, a progressive cooling displaces "up" the base line with a "reduction" of the accessible hysteresis cycle. See, for instance, Figure 1.

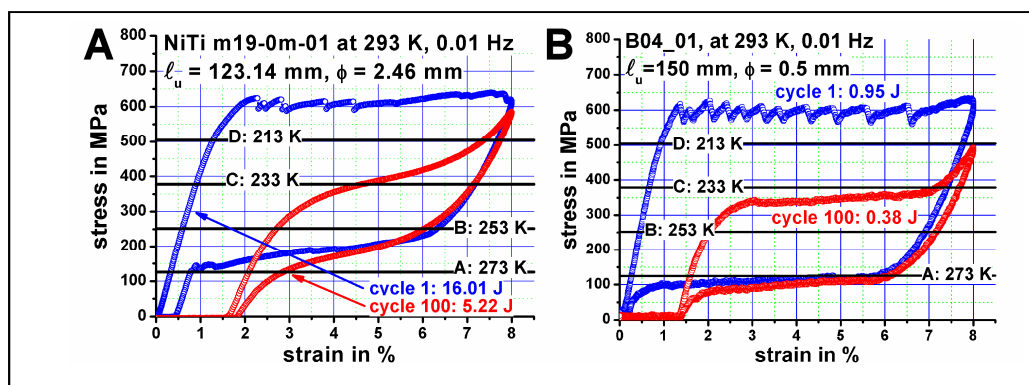


Figure 1. Preliminary position effect on the "baseline" of NiTi hysteretic behavior for winters at 273 (A), 253 (B), 233 (C) and 213 K (D). A: sample of diameter 2.46 mm; B: sample of diameter 0.5 mm.

Figure 1 shows the position of each reference line associated to different working temperatures and visualizes the differences between the wires of diameter 2.46 (Figure 1A) and 0.5 mm (Figure 1B). After the training, the former one shows an S-shaped cycle, whereas the latter one remains with the flat cycles. Figure 1A clearly establishes that, at 253 K, the upper part of the hysteretic behavior, between 250 and 600 MPa, is preserved. After the cycle 100, an available net strain of about 6% remains when the SMA creep (close to 2 %) is suppressed. On the contrary, using the 0.5 mm wire at 273 K or at lower temperatures, the sample can transform but without any return to parent phase. The pseudo-elastic behavior disappears and, after transformed, the NiTi wire remains “completely” in the martensite phase.

The action of external forces induces in the SMA wires a first order phase transformation between metastable phases i.e., a martensitic transformation, with a hysteretic behavior. The transformation is modified by the action of the CCC due to either the external temperature effects or the internal actions (i.e., self-heating) associated to the dissipated latent heat in the working cycles. The value of CCC for the NiTi wires is estimated close to 6 MPa/K [9, 10] (see Figure 2A).

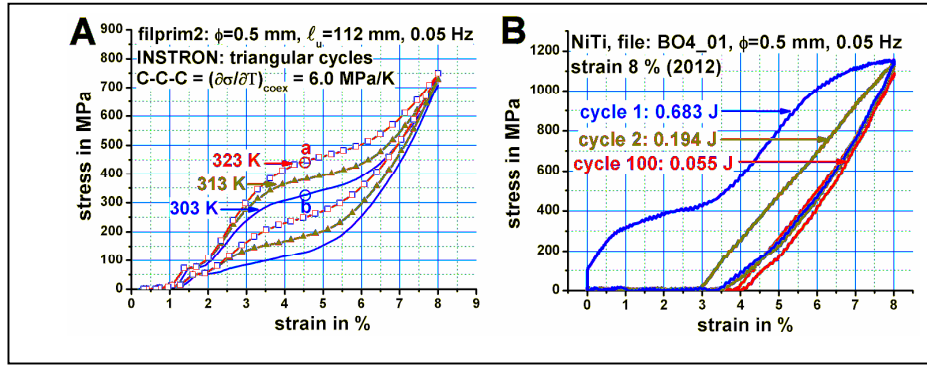


Figure 2. A: The external temperature changes, i.e., the Clausius-Clapeyron effect, in a NiTi wire of diameter 0.5 mm. B: cycling in martensite. Loading in cycle 1 shows hysteresis associated to martensite reorientation with minor effect in cycle 2. During the unloading the sample remains in martensite. In cycle 100, the hysteresis is practically zero.

For alloys with a hysteresis cycle well situated for working in the neighbors of the room temperature (i.e., 293 K), the effect of cold winters can be negative in terms of the damping action. The “classical” behavior of thinner NiTi wires shows flat cycles at 233 K with the SMA wire completely converted in martensite. For instance, the cycle 100 in Figure 1B remains in martensite after a transformation induced by stress and realized at 273 K. Further reduction of temperature converts directly the pseudoelastic NiTi to martensite without any hysteretic behavior (Figure 2B). Hence, the measurements taken, for instance, at IFSTTAR in the cold winter of 2010 demonstrate a satisfactory dampers performance which is peculiar of the wires with 2.46 mm of diameter. Instead, the wires of 0.5 mm cannot work at working temperatures below 273 K.

This work focuses on four types of actions in the SMA alloys. First, the temperature effects induced by self-heating in the SMA specimen are investigated, i.e., the effects of temperature increasing with the cycling frequency. The second one is associated to external temperature effects; the aim is to verify the appropriateness of the NiTi wires of diameter 2.46 mm for temperatures overcoming 253 K. The third type of effects relates to the “static” and irreversible aging actions in NiTi. The temperature aging modifies the phase transformation temperatures, whereas the stress aging produces permanent effects which increase the working domain from 600 to 900 MPa. The fourth type describes the dynamic and recoverable actions in SMA, mainly with reference to CuAlBe, i.e., a Cu-based alloy.

II. SELF-HEATING AND/OR INTERNAL TEMPERATURE EFFECTS

For our experimental study, focused on engineering applications, we used a NiTi alloy in the pseudo-elastic state, furnished in several orders and years: in the time period from 2007 to 2012, by Memry (CT, USA) and a division of SAES Getters (Italy); previously (2004-2007) by Special Metals Corp (New Hartford, New York, USA). Wires of two diameters were studied. For the A wires with a diameter of 2.46 mm, the surface of the samples was finished in a light (gray) oxide surface. For the B wires with a diameter of 0.5 mm, the surface was covered by black oxide. According to the supplier remarks, the austenite starting (A_s) phase temperatures were similar; namely, 248/247 K and 243 K, respectively. The nominal composition was 55.95 wt% Ni balance Ti. Evaluation of the Clausius-Clapeyron coefficient establishes a value close to 6 MPa/K for the A and for the B wires. See, for instance, the ref. [10].

The experimental results aiming to characterize the self-heating effects are reported in Figure 3. The cyclic (sinusoidal) measurements are induced on the NiTi samples by an INSTRON equipment, and the temperature measurements are realized by a K-thermocouple wrapped around the sample. The effects of a progressive increase of the cycling frequency on the temperature measurements are reported in Figure 3A for a maximum strain of 8%. At 0.01 Hz, the local temperature oscillates around the room temperature of about ± 10 K. At 1 Hz, the maximum temperature change overcomes 20 K. It reaches 30 K

when cycling at 3 Hz. These measurements are useful to identify possible difficulties related to the Clausius-Clapeyron coefficient. For instance, an excessive temperature change of 30 K indicates an increase of 180 MPa in the maximum stress and, obviously, a relevant reduction in the fracture life.

A satisfactory increase of the fracture life is obtained when working at low levels of strain. The plots in Figure 3B are associated to a reduced strain of 1.8 %. With respect to the previous measurements at 8% strain (Figure 3A), lower values of local temperature are reported in Figure 3B for the measured cycling frequency of 1, 3, 5, and 10 Hz. The effects of airflow further reduce the local temperature values to one half. These measurements suggest that the spontaneous cooling and the reduced oscillation amplitudes associated to the normal operating conditions of a bridge permit a SMA damping action adequate to mitigate the cable oscillations induced by wind or rain. For strains of 1 and 0.8 % and cycling frequencies of 8 and 16 Hz, respectively, the local temperature effects do not overcome 10 K (Figure 3C). Hence, for reduced strains ensuring a large fracture life, the quantified effect can be neglected.

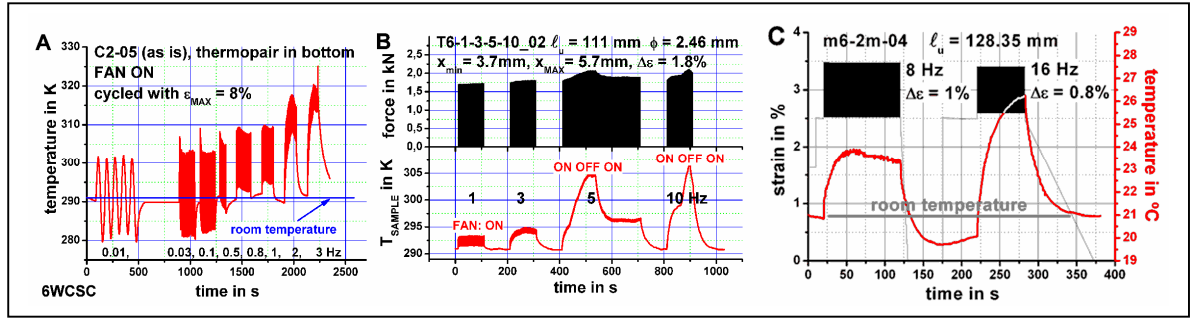


Figure 3. The self-heating (i.e., local temperature) effects measured against time at varying cycling rates and deformation values.

III. EXTERNAL TEMPERATURE EFFECTS

The studies realized at IFSTTAR, near Nantes, France, shows excellent damping using two short NiTi wires of diameter 2.46 mm (Figure 4). The measurements were realized in the frame of SMARTer project of the European Science Foundation. The hysteretic behavior of the SMA wires produces a force slowly decreasing with the strain increase. The change on the SMA force modifies the frequency of the system, i.e., the cable and the damper. See, for instance, the curved solid line in Figure 4 B.

The experimental observations establish that the SMA wires work efficiently in smoothing the oscillations induced by transitory actions. Indeed, the extreme pulse actions disappear in 10-12 s. The measurements at IFSTTAR were collected outside the laboratory, under the action of external temperature effects. A set of measurements was realized in December 2010, an “extremely hard” winter for Western Europe. Permanent iced snow is present near the cable in the 4 days (26-29) of measurements. The effects of a mean temperature in the cable continuously under 270 K result in some difference with the measurements taken in the October 2009 (Figure 4B). The SMA response is more slow and coherent with the presence of a little quantity of martensite in the SMA wires. Nevertheless, the measurements realized at IFSTTAR in December 2010 with an iced external temperature establish satisfactory damping effects.

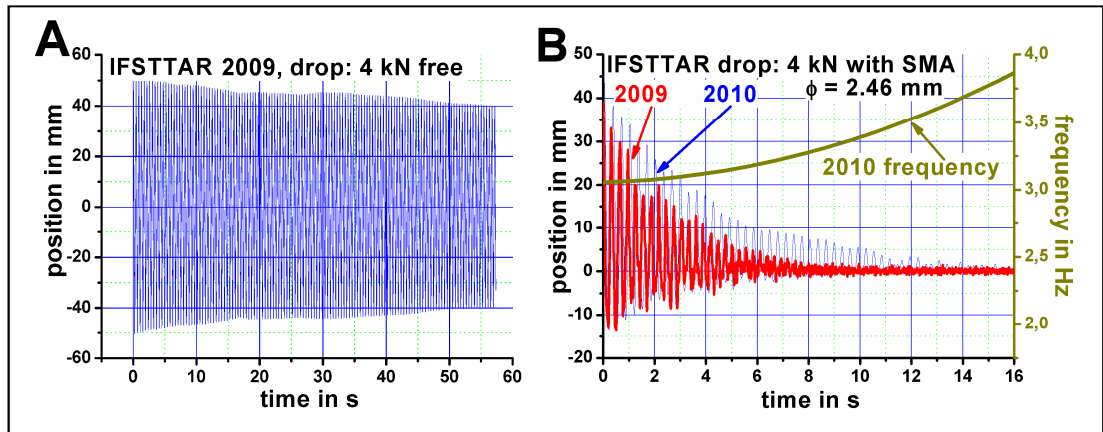


Figure 4 Results from the IFSTTAR measurements. A: free cable oscillations. B damped signals. Continuous solid line labelled “2010 frequency”: frequency evolution.

A further series of measurements was programmed to characterize the appropriateness of using the NiTi wires for the bridges in colder climates, as in Northeastern Europe. The effects of temperature changes on the SMA behavior are outlined in Figure 5. Continuous cycles at 20 s/cycle and with a maximum net strain of 5 % are realized in a preliminarily trained sample. The hysteretic energy (Figure 5A, top) tracks the sample temperature (Figure 5A, bottom). The dissipated energy is estimated at several points (labelled as A, B, C, D, and E) along the recorded time histories in Figure 5A. The corresponding hysteresis cycles and associated temperatures are reported in Figure 5B.

The measurements establish that, at low temperatures, the NiTi wire with an S-shaped cycle works satisfactorily but at a reduced net strain due to the martensite formation. The results in Figure 5 suggest that the sample behavior remains appropriate for the considered damping applications for temperatures as low as 253 K and net strains between three and five per cent. Working at “higher temperatures” as, for instance, at 335 K, the material remains completely in parent phase thus producing a complete hysteresis cycle.

The observation that the use of dampers based on trained NiTi wires with hysteresis cycles similar to cycle 100 in Figure 1A permits satisfactory damping at temperatures as low as 253 K is associated to the S-shaped aspect of the hysteresis cycles and to the maximum stress available (600 MPa in Figure 1A). For working in northeast Europe or South Canada, an effective damping action is required at lower working temperatures, i.e., 233 K or less. An extension of the temperature span can be achieved by an increase of the maximum stress available up to 900 or 1000 MPa, as the one resulting, for instance, from the stress-temperature aging described in the next Section.

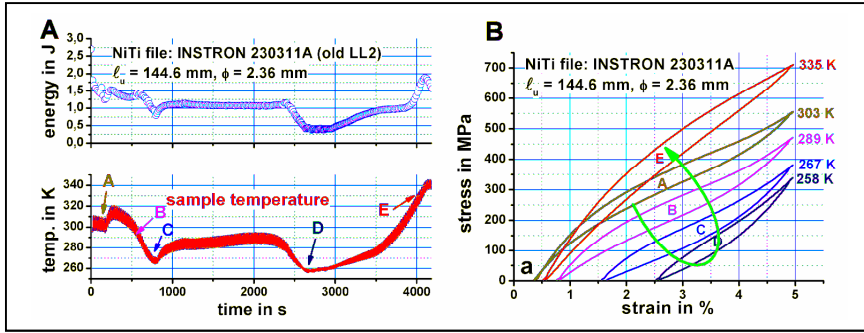


Figure 5. Effects of the external temperature changes on the dissipated energy and the S-shaped hysteresis cycle of the NiTi wire.

IV. TEMPERATURE AGING AND STRESS-TEMPERATURE AGING

When the dampers are situated in a ceramic roof (as in the Basilica of San Francesco in Assisi, Italy), the external temperature can overcome 350 K in summer. A preliminary study of the temperature aging effects is necessary to ensure that the heating of the roof does not produce negative effects on the damper behavior. The results in Figures 6A and 6B are associated to the aging at a high temperature of 373 K. A classical process in SMA consists of two frequent consecutive phase transitions from parent to R and, after, to martensite. The calorimetric and the electrical resistance measurements establish that the temperature aging induces a non-recoverable, or irreversible, increase of 10-20 K/year in the phase R starting temperature (R_s). Hence, the net effect is a monotonic increase in R_s as a function of the aging time [11]. See, for instance, the effect by comparing the A, B, C and D curves in Figure 6A. The value remains constant when the aging temperature decreases (this action is different from the one observed in the Cu-based alloys, which tracks the aging temperature). In Figure 6C, a “complete” calorimetric measurement between 300 and 100 K visualizes the beta-R transition previous to the R-martensite transition in cooling.

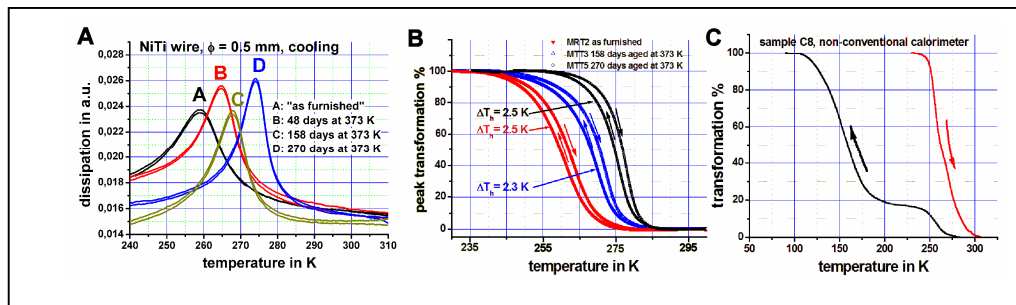


Figure 6. Temperature aging at 373 K: changes in R_s against aging time via a standard Differential Scanning Calorimetry (DSC), i.e., cooling to 193 K, and via an unconventional DSC cooling down to 100 K. A: Calorimetric outputs for different aging durations of 0 days (A: as furnished), 48 days (B), 158 days (C) and 270 days (D). B: hysteretic phase transition cycles. C: behavior of two transformations (parent to R and, after, to martensite).

The experimental measurements show that the temperature aging at zero stress does not modify the stress-strain cycles. The focus of this study is then placed on the stress-temperature aging with the task of achieving a possible increase of the maximum stress in the S-shaped cycles. Indeed, some preliminary results [5] outline an eventual increase of the maximum stress in appropriately strain-aged samples. The beneficial effect consists of lowering the minimum working temperature of the dampers, thus resulting in an applicability improvement.

A preliminary study of the effect of the stress-aging was performed by placing a NiTi sample of length 1010 mm and diameter 0.5 mm under a strain of 4.5 % at 292 K for 27 days [11, 12]. Some increase in the stress was required to continue and to complete the transformation. Moreover, the next cycle required a reduced stress in the previously transformed zone. The complete stress step with similar increase and decrease was close to 35-40 MPa.

In the present work, samples of length 180 mm and two different diameters of 0.5 and 2.46 mm, respectively, are considered for the stress-temperature aging studies. A dedicated device was conceived and built to perform an appropriate stress-temperature aging for several months. In Figure 7A, the items A and A' are the two pairs of cubic blocks that fasten the edges of the sample labelled as "c", and they can be adapted to the wire diameter. The items B and D refer to the screw and the associated bolt, respectively. An appropriate pin permits to displace the screw B only. As a consequence, turning the bolt D around the screw B, the length of the sample is modified by the displacement along the axis of the screw. The device hosting the sample is then situated for long time-intervals inside a furnace at constant temperature, for instance, at 373 K. The aging is performed at constant deformation, i.e., it is a "static" process.

After aging, the stress-strain working cycles are performed by placing the device hosting the sample in a conventional MTS 810 equipment that works at room temperature in an air-conditioned room (293 K). The positioning of the device when working in traction is shown in Figure 7B. It is accomplished by means of two auxiliary elements (labelled as C and C' in Figure 7B) which are screwed to the cubic edges of the device. The use of the same device during the aging and in the MTS equipment avoids the parasitic effects created by the grips when mounting and dismounting the sample. For this reason, the shape of the samples is strictly cylindrical without the classic "bone shape" commonly adopted to cope with the fixing difficulties.

In Figure 7B, "a" is the room-temperature thermocouple situated in the neighboring of the sample. Furthermore, it is possible to situate a K-thermocouple in the sample (c) for measurements of the sample temperature and its evolution under the MTS cycles.

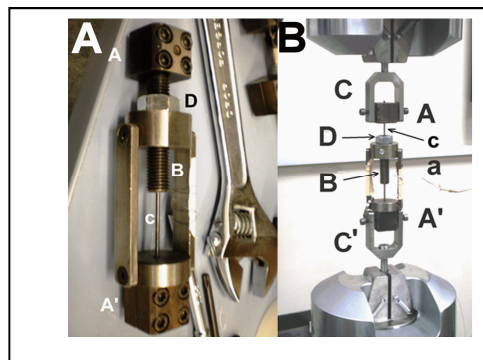


Figure 7. The device conceived for stress-temperature aging: dismantling the sample is not necessary for cycling in the MTS. A, A': the two pairs of cubic blocks that fasten the edges of the NiTi wire (sample "c"). B and D: the screw and the associated bolt that allows to modify the length of the sample by stress. (b): positioning of the device when working in traction and using a conventional thermo-mechanical equipment. C and C': auxiliary grips. "a": room temperature thermocouple.

A. NiTi wires of diameter 2.46 mm

The stress-aging effects are illustrated in Figure 8 for several samples of diameter 2.46 mm. The tested samples are either preliminarily aged or considered as furnished. The aged samples are subjected to different levels of constant deformation, between 3% and 8%, and placed at 373 K for different periods of time (more than one month). The stress-temperature aging is performed under "static" conditions, i.e., the samples remain stressed at a constant strain and temperature. A complete characterization of the stress-temperature aging including the eventual dynamic actions is beyond the scope of this work. After stress-aging, the samples are mechanically cycled. The dotted curves in Figure 8A are plotted as reference to visualize the initial cycles and emphasize the changes from cycle 1 to 100. The action of 100 sinusoidal cycles realized up to a strain of 8% at 0.01 Hz induces a S-shaped hysteresis cycle with a creep of about 2%.

From Figure 8, the effects of higher levels of constant deformation and a longer duration of the stress-aging process are clearly important. Figure 8A shows the comparison for the cycles 1 and 100 between the as-received sample without aging and a sample with three months at 373 K and under a constant strain of 4.5%. It can be seen that the first cycle is clearly affected, but after 100 cycles, the changes in the shape of the hysteresis curve due to aging effects are negligible. Only minor actions appear in the form of a hysteresis width reduction and a reduced increase of the maximum stress value. Figure 8B shows the results for an as-received sample without aging and a sample with 54 days under a strain aging of 6.8% at 373 K. In

this case, the effect is permanent. The hysteresis shape in the first cycle is clearly modified, and after 100 cycles, the width is reduced, but the maximum stress still remains close to the initial value. Figure 8C shows the changes after 7.5 months at 6.8% and 373 K. In cycle 1, the maximum stress is increased up to 1000 MPa. After 100 cycles, this value of maximum stress decreases of about 50 MPa, and the hysteretic width is reduced.

The measurements suggest that a relevant effect of the stress-temperature aging at 373 K appears for levels of constant strains corresponding to completely transformed samples. Furthermore, the effect is enhanced by protracting the time elapsed in the strained state. Previously cycled samples show similar effects, without large changes in the hysteresis related to cycling from cycle 1 to 100. For a preliminary study of the permanence of the ageing effects, supplementary cycling is performed for the same samples after two years in the laboratory with equivalent results. Hence, the effects induced by an adequate stress-temperature ageing are permanent, and they can be considered as irreversible changes in the NiTi samples.

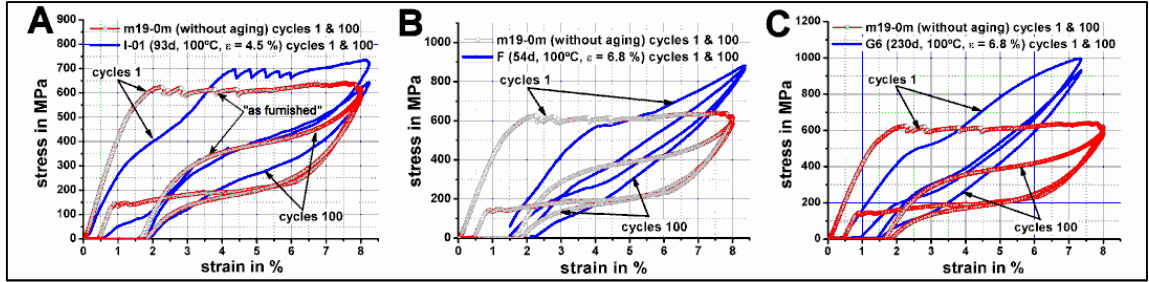


Figure 8. Results of stress aging at 373 K for NiTi wires of diameter 2.46 mm. Empty dots: “as furnished” samples. Solid line: stress aged samples. A: 3 months aging at a strain of 4.5%; B: near 2 months aging at a strain of 6.8 %; C: 7 months of aging at a strain of 6.8 %.

B. NiTi wires of diameter 0.5 mm

In Figure 9, two examples of the stress aging results obtained for NiTi wires of diameter 0.5 mm are reported. As shown in Figure 9A, four months at 2% constant deformation induce an extremely reduced action. The transformation of the first cycle shows a minor reduction of the “parent” strength, i.e., of the mean slope. See, for instance, the circled zone in Figure 9A. The ripple in the transformation is a nucleation effect, similar to the effects observed in the wires of 2.46 mm. After 100 cycles, the shape of the hysteretic cycle observed for the stress-aged sample approaches the one obtained for the sample tested as-received. Hence, the stress aging action almost entirely disappears.

The effect of the stress-aging performed at a higher level of constant strain (i.e., 8 %) and for a duration of 4 months at 373 K is more relevant (Figure 9B). The experimental results suggest that, in this case, the aged sample is completely converted into martensite phase. The cycle 1 (labelled as “a” in Figure 9B) shows the classic behavior associated with the reorientation of martensite in the applied stress direction. Cycle 100 (labelled as “b” in Figure 9B) is practically elastic with no significant hysteresis. It is worth noting that an increase of the temperature in the furnace system of the INSTRON machine returns the alloy to parent phase with a standard cycling.

The results suggest that the thinner wire with the flat cycles cannot produce damping at lower temperatures. At 273 K, the NiTi sample transforms and remains in martensite without retransformation. As shown in Figure 9B, aged samples of 0.5 mm diameter under 8% strain are completely converted in martensite. The measurements suggest that the stress-temperature aging effect induces a global increase in the martensite starting transformation temperature (M_s). In fact, after aging the sample under a constant strain near 8%, the mechanical cycling cannot show significant hysteresis, as depicted by the curve “b” in Figure 9B. Hence, similar actions can produce extremely different results for different diameters. In other words, classical scaling techniques are not appropriate when modelling SMA elements. Hence, ensuring the adequate working applications requires a deep analysis of the used materials.

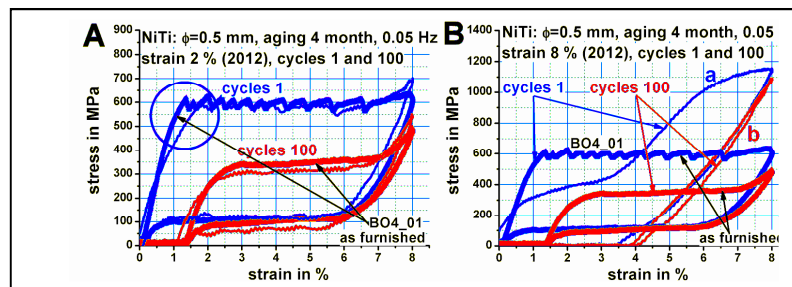


Figure 9. Stress-temperature-aging effects for NiTi wires of diameter 0.5 mm. A: Comparison between a sample tested “as furnished” and a sample aged for 4 months under a strain of 2% (see circled zone). B: Comparison between a sample tested “as furnished” and a sample aged for 4 months under a strain of 8%. Cycle 1 (a) shows martensite deformation without any retransformation. Cycle 100 (b) shows irrelevant hysteresis.

V. PRELIMINARY ANALYSIS OF DYNAMIC ACTIONS ON SMA

The copper-based alloys, such as CuZnAl and CuAlBe, are more “sensitive” than NiTi to the effects produced by the dynamic actions related to fast cycling. In the Cu-based alloys, a martensite stabilization effect is typically observed. In stabilized samples, a large hysteresis reduction occurs and, in fact, the sample cannot recover the parent phase. Only a homogenization can recover the initial parent state. The effects of performing partial cycling (i.e., a cycling that is too fast to permit the complete transformation) and internal loops are shown in Figures 10A and 10B, respectively, for a CuAlBe polycrystalline alloy. Cycling at 2 and 1 Hz, respectively, decreases progressively the mean stress of the transformation.

The observations at constant temperature related to recoverable dynamic actions are particularly relevant in single crystals of Cu-based alloys [13]. The results associated to partial cycling of a single crystal CuAlBe alloy are shown in Figure 11A. Progressively the stress decays to zero, and the cycled part progressively remains in martensite, thus undergoing a sort of “dynamic stabilization”. The effects on the cycles associated to a complete transformation are shown in Figure 11B. After 1300 fast cycles, a creep of 2% strain is stabilized but, after one day of pause at zero stress, the hysteretic behavior recovers and clearly approaches its initial shape. As mentioned above, the dynamic effects are clearly evident in Cu-based alloys, but only minor actions can be visualized in NiTi wires (Figure 12). When a pause is performed within a series of working cycles, the next cycle transforms with an extremely little recovery.

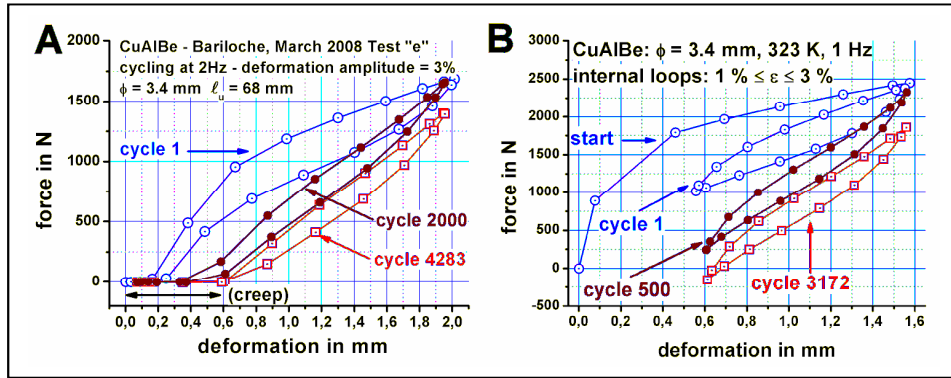


Figure 10. Partial cycling in a CuAlBe polycrystalline alloy. A: partial loops up to 3% showing a progressive decrease of the mean force (i.e., the stress) against the number of cycles. B: internal loops (between 1 and 3 %) with similar behavior against the number of cycles.

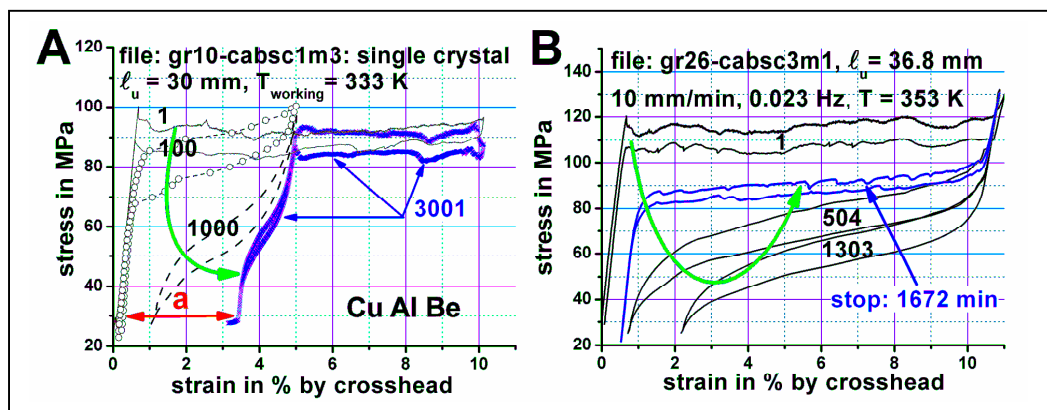


Figure 11. Dynamic stabilization and recovery in a single-crystal CuAlBe alloy. A: Cycle 1 and the first cycle after 3000 rapid cycles are shown in solid lines (crosshead speed: 0.1 mm/min). Cycles 100 and 1000 are performed at 20 mm/min and plotted in dotted and dashed lines, respectively. The test temperature is 333 K. The curved arrow shows the evolution associated to the cycling process (from 1 to 3001). A: Dynamically stabilized martensite. B: Slow cycles obtained with a crosshead speed of 0.1 mm/min: cycle 1 and one “recovery cycle” obtained 1672 minutes after 1303 rapid cycles. Two rapid cycles (504 and 1303) obtained at a crosshead speed of 10 mm/min are also shown. The curved arrow follows the evolution associated to the “fast” cycles and to the recovery related to one stop after the first 28 h.

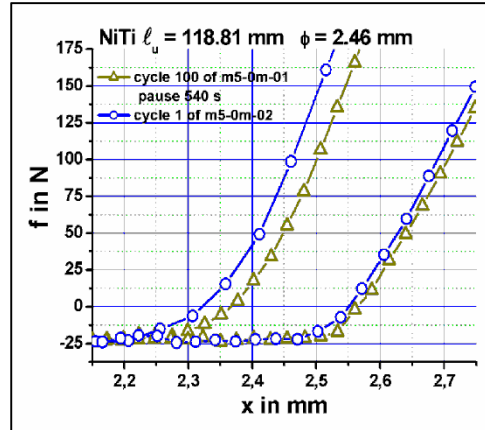


Figure 12. Increase of the SMA creep for a large series of working cycles. In a NiTi wire of diameter 2.46 mm, only a minor creep reduction is achieved after a pause of 540s.

VI. CONCLUSIONS AND REMARKS

The hysteretic S-shaped behavior from 0 to 600 MPa observed at room temperature allows for effective partial cycles at low external temperatures. Even lower temperatures can be considered as adequate working conditions when using properly aged samples with a higher value of maximum stress associated to the full transformation. Progressive cooling establishes a gradual increase in the quantity of martensite with a corresponding progressive reduction of the quantity of the parent phase and a reduction of the hysteresis cycle. For a maximum stress value of 600 MPa, the working temperature domain permits the use of the damper in winter weather (i.e., for a temperature as low as 258 K) [6]. In extreme colder climates, the temperature variation between summer and winter can approach 80 K, with a lower temperature of 233 K. The aging results for strains near 8% establish that an increase in the aging time from 2 to 7.5 months induces an increase in the maximum stress value. Changes in the maximum stress up to 800-1000 MPa are beneficial because they permit the damping action in extremely cold temperatures. Indeed, a maximum value of 600 MPa suggests a reasonable behavior for temperatures as low as 253 K, but for aged samples with 900-1000 MPa the permitted working temperatures are as low as 233 K.

The different results obtained for wires of different diameter are analyzed. The stress-aging induces an increase of M_s that progressively decreases when the radius increases. A detailed study of the structural characteristics will be the object of future research work, with the awareness that the structural changes associated to "minor" effects on the transformation temperatures (i.e., M_s) are very small and, actually, under the resolution limit. The action of quench in single crystals of Cu-based alloys changes the M_s by, for instance, 50 K. Structurally, the evolution is observed by neutrons and positrons [14, 15]. Minor actions of the tracking between the M_s and the external temperature are observed in single crystals working in the resolution limit using neutrons in the ILL facility (Grenoble, France) [16, 17]. In fact, the changes in M_s of SMA are much more sensitive than the structural changes.

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